Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: A critical meta-survey

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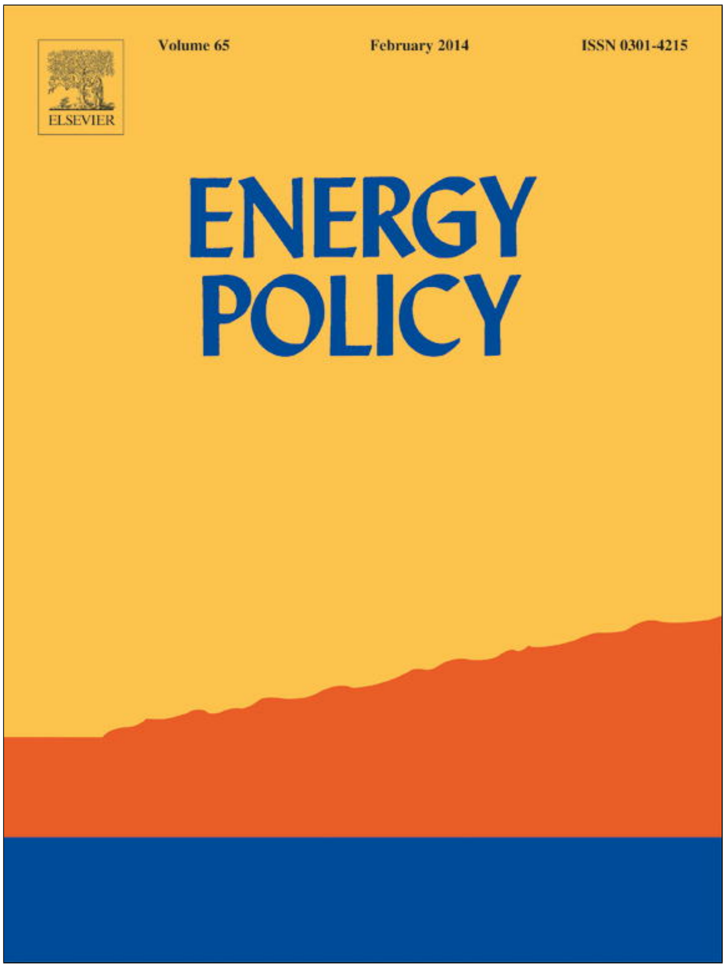
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Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: A critical meta-survey

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HIGHLIGHTS

- This article screens 153 lifecycle studies of wind and solar energy.
- Wind energy emits 0.4 g CO_2-eq/kWh to 364.8 g and a mean of 34.11 g.
- Solar PV emits 1 g CO_2-eq/kWh to 218 g and a mean of 49.91 g.

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ABSTRACT

This paper critically screens 153 lifecycle studies covering a broad range of wind and solar photovoltaic (PV) electricity generation technologies to identify 41 of the most relevant, recent, rigorous, original, and complete assessments so that the dynamics of their greenhouse gas (GHG) emissions profiles can be determined. When viewed in a holistic manner, including initial materials extraction, manufacturing, use and disposal/decommissioning, these 41 studies show that both wind and solar systems are directly tied to and responsible for GHG emissions. They are thus not actually emissions free technologies. Moreover, by spotlighting the lifecycle stages and physical characteristics of these technologies that are most responsible for emissions, improvements can be made to lower their carbon footprint. As such, through in-depth examination of the results of these studies and the variations therein, this article uncovers best practices in wind and solar design and deployment that can better inform climate change mitigation efforts in the electricity sector.

1. Introduction

Herman Scheer, a former German Parliamentarian and influential renewable energy advocate, once stated that "[o]ur dependence on fossil fuels amounts to global pyromania… [a]nd the only fire extinguisher we have at our disposal is renewable energy" (Connolly, 2008). Scheer is famous for his work in creating Germany's renewable energy feed-in-tariff scheme and the ensuing adoption of solar photovoltaic and wind energy projects across the country. Although there are a number of options to reduce global dependence on fossil fuels that Scheer could have referred to, renewable sources of energy such as wind turbines and solar panels were his solution. This leaves at least one primary question to be resolved: how can we most effectively use the fire extinguisher?

To provide some answers, this study considers one of the most important aspects of our fossil fuel pyromania, the climate change implications of electricity generation. It assesses how two prominent renewable energy resources, solar photovoltaics (PV) and wind turbines, emit greenhouse gases (GHG), and it also offers suggestions for how such technologies can best be utilized or improved to mitigate climate change. By critically evaluating the current literature regarding lifecycle GHG emissions stemming from the full range of PV and wind electricity generation technologies, this study seeks to determine what the average lifecycle emissions are, where the emissions falls in terms of lifecycle stages, and what factors cause overall GHG variation in the literature, and can therefore be used to create the most effective climate change mitigation options.

Our assessment reveals the following. Within the "best" sample of 41 articles evaluated, the average lifecycle greenhouse gas emissions for wind energy were 34.1 g CO_2-eq/kWh, whereas solar PV averaged 49.9 g CO_2-eq/kWh. Essentially, these measures represent the amount of GHGs released in grams for each kWh of electricity that the technology provides, illustrated in Fig. 1.

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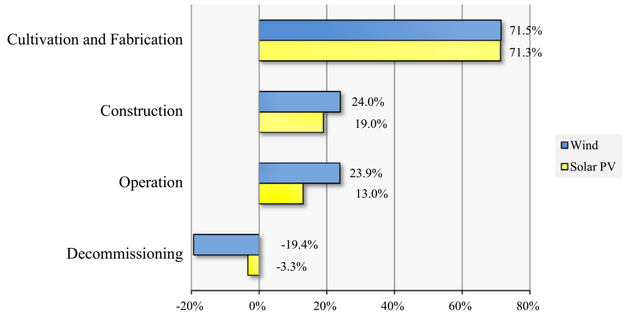

Fig. 1. Breakdown of lifecycle greenhouse gas emissions for wind energy and solar PV (% of total).

As that figure reveals, cultivation and fabrication are responsible for the largest share of emissions for both technologies, followed by construction and operation. Decommissioning practices often recycle materials from both systems back into future production processes, thus most studies argue that this constitutes an emissions "sink" that lowers the greenhouse gas profile for both types of systems.

To make its case, the article proceeds as follows. It starts by introducing readers to the specific lifecycle stages of both onshore and offshore wind turbines and solar photovoltaic panels. It then explains the research methods utilized by the authors to distill from 153 studies 41 of the most relevant, recent, peer-reviewed, original, and complete assessments. The next part of the article presents the findings from this selection process before explaining the factors behind the disparity in estimates for both wind and solar energy systems, and offering salient conclusions for technological entrepreneurs and energy policy analysts.

2. Explaining lifecycle stages

Generally, a lifecycle analysis determines a particular facet (functional unit) of an object, process, or product over the entire course of that subject's existence (Dale, 2013). For this particular study, that subject is both wind and solar photovoltaic electricity generators, and the functional unit by which both are examined is the GHG intensity in terms of grams of CO_2-equivalent emissions per kilowatt-hour (CO_2-eq/kWh) produced. Assessing the emissions of both PV and wind leads to a particularly broad categorization of what constitutes a lifecycle stage. Nonetheless, the literature suggests that four of those stages are salient: material cultivation and fabrication, construction, operation, and decommissioning. This section discusses each in turn.

2.1. Material cultivation and fabrication

In general, the material cultivation and fabrication stage represents the broadest group as it incorporates the full range of resource extraction, processing of materials, and the amalgamation of final products. Although details vary based upon the type of PV module, for instance (thin film, mono, poly, or multi-crystalline, dye-sensitized, quantum dot, and so on), material cultivation encompasses mining, refining and purification all of the silicon and/or other required metals and minerals for the cells, glass, frame, inverters, and other required electronics. Petroleum extraction for plastics, natural gas extraction used for heating, and effectively any other material extraction and processing needed to create the PV module and finished electronics are also included. Finally, the wiring, encapsulation and any other processes by which the modules and electronics are fabricated and finished (up until the point of transportation to the site of operation) are all included in this part of the stage for PV. Applying essentially the same concept to wind energy means metal and petroleum extraction for steel, plastics, internal wiring, etc., are included. Furthermore, composition and production of the blades, gears (although there are also gearless turbines), rotors, nacelle, turbine, and tower are all part of this stage.

2.2. Construction

A second stage involves the on-site construction of the generator and transportation of materials to the site. For PV, encompasses transporting the panels, and installing them along with the balance-of-system (BOS), including mounting structures, cabling and interconnection components, and inverter (although the exact BOS assumptions vary by study). GHG emissions for this stage thus include the processing of BOS materials and fossil fuels burned in transporting and assembling the system. For wind power, transportation and BOS includes a significant amount of cement and iron rebar to support structures, as well as cabling and construction of substations, when necessary.

2.3. Operation and maintenance

Operation is the third stage, and perhaps the most straightforward. Operation of solar PV includes maintenance, perhaps some minor replacements when necessary, cleaning of the modules, and any other processes that occur while the panels are in use. Essentially the same applies for wind, including regular maintenance and cleaning, possible replacement parts such as blades and gear components, and required material inputs such as hydraulic oil and oil filters used to lubricate turbines.

2.4. Decommissioning

Decommissioning is the final stage that essentially involves the deconstruction processes, disposal, recycling and (possibly) land reclamation. Because recycling is effectively a means of mitigating future GHG production, many of the studies we reference below consider this stage to decrease the total GHGs produced over the lifecycle of the generator. For instance, reclamation is not a standard practice for wind energy (the pads are often left or reused), and a majority of the steel towers, plastics, and fiberglass blades are recyclable. Accordingly, the process carries with it some significant offsetting of future emissions.

3. Research methods and selection criteria

To ensure that only the "best" peer-reviewed scientific literature was selected, as many on-topic studies as possible were collected by searching eight academic databases—Jstor, Science-Direct, EbscoHost, Energy Citations Database, Web of Science, Water Resources Abstracts, Science Abstracts, and ProQuest abstracts (including Sustainability Science Abstracts and Engineering Abstracts)—between January 2013 and April 2013. The following terms were searched within the title, abstract, or keywords of a study: "lifecycle," "life-cycle," "life," "cycle," "analysis," "LCA (lifecycle analysis)," "GHG," "greenhouse gas," "green-house gas," "green house gas," "carbon dioxide," "CO2," "solar," "PV," "wind," "energy," "electricity," "renewable," and "resources." Generally some variation of the terms lifecycle, greenhouse gas, and solar and/or wind constituted the most effective searches.

These searches resulted in 153 lifecycle studies. To narrow within this broad base to a more robust sample, we filtered the literature to ensure that only the most relevant, modern, accurate and original findings were incorporated into this study. Fig. 2

Fig. 2. Selection process for determining the best lifecycle studies for wind and solar energy. *Note*: Articles excluded for "relevance" refer to those articles that failed to provide any lifecycle GHG intensity estimates. Those excluded by "date" signifies an article published prior to 2003. Those excluded for "peer-review" could not be shown to have undergone any type of review prior to publication. Those excluded for "originality" refer to articles which provided no original GHG intensity analysis and merely relied on estimations contained in prior studies. Articles excluded for "completeness" only considered CO_2 lifecycle emissions, not the full range of GHGs in terms of CO_2-eq.

Table 1
Lifecycle studies excluded for relevance.

Source	Technology
Akyuz et al. (2011)	Wind, solar PV
Amor et al. (2010)	Wind, solar PV
Appleyard (2009)	Solar PV
Ardente et al. (2005)	Solar PV
Barrientos Sacari (2007)	Solar PV
Belfkira et al. (2008)	Wind, solar PV
Blanc et al. (2012)	Wind
Branker et al. (2011)	Manufacturing
Browne (2010)	Wind
Burger and Gochfeld (2012)	Wind, solar PV
Chel et al. (2009)	Solar PV
Crawford (2009)	Wind
Delucchi and Jacobson (2011)	Wind, solar PV
Espinosa et al. (2011b)	Solar PV
Espinosa et al. (2012)	Solar PV
Fthenakis (2004)	Solar PV
Fthenakis et al. (2009a)	Solar PV
Granovskii et al. (2007)	Wind, solar PV
Gustitus (2012)	Wind
Himri et al. (2008)	Wind
Huang et al. (2012)	Solar PV
Jacobson and Delucchi (2011)	Wind, solar PV
Kaldellis et al. (2012)	Wind, solar PV
Kammen (2011)	Solar PV
Katzenstein and Apt (2009)	Wind, solar PV
Kreiger et al. (2013)	Solar PV
Kubiszewski et al. (2010)	Wind
Limmeechokchai and Suksuntornsiri (2007)	Wind, solar PV
Lindstad et al. (2011)	Shipping
Lundahl (1995)	Wind, solar PV
Marimuthu and Kirubakaran (2013)	Wind, solar PV
Martinez et al. (2009b)	Wind
Martinez et al. (2010)	Wind
Martinez et al. (2012)	Wind, solar PV
Mason et al. (2006)	Solar PV
Matsuhashi and Ishitani (2000)	Solar PV
McCubbin and Sovacool (2013)	Wind
Mendes et al. (2011)	Solar PV
Mohr et al. (2009)	Solar PV
Muller et al. (2011)	Wind, solar PV
Nandi and Ghosh (2010a)	Wind
Nandi and Ghosh (2010b)	Wind
Oke et al. (2008)	Solar PV
Ou et al. (2011)	Wind, solar PV
Pearce (2002)	Solar PV
Pieragostini et al. (2012)	Lifecycle Methodology
Rashedi et al. (2012)	Wind
Raugei and Frankl (2009)	Solar PV
Rubio Rodriguez et al. (2011)	Wind
Silva (2010)	Wind, solar PV
Sioshansi (2009)	Energy technology
Tokimatsu et al. (2006)	Nuclear
Tripanagnostopoulos et al. (2005)	Solar PV
Vadirajacharya and Katti (2012)	Wind, solar PV
Velychko and Gordiyenko (2009)	GHG inventories
Vuc et al. (2011)	Wind, solar PV
Whittington (2002)	Wind, solar PV
Zhai et al. (2011)	Wind, solar PV

Table 2
Lifecycle studies excluded for recentness.

Source	Technology	g CO_2/kWh
Huber and Kolb (1995)	Solar PV	–
Kato et al. (2001)	Solar PV	14–9
Kemmoku et al. (2002)	Wind, solar PV	–
Kreith et al. (1990)	Solar PV	–
Lenzen and Munksgaard (2002)	Wind	–
Norton et al. (1998)	Solar PV	–
Schleisner (2000)	Wind	9.7–16.5
Sorensen (1994)	Wind, solar PV	–
Van de Vate (1997)	Wind, solar PV	–
Voorspools et al. (2000)	Wind, solar PV	–

shows that, through this process, the application of five selection criteria whittled our sample down to only 41 of the "best" studies. The following subsections detail this selection process.

3.1. Relevance

The first exclusionary step entailed removing a total of 58 articles based upon relevance. These studies, shown to the left in Table 1, did not specifically address lifecycle GHG emissions of either wind or solar, or else did not provide necessary information, such as total emissions and total electricity produced, that could be used to easily find that value. While there were many comprehensive and competent studies among those excluded for this reason, they primarily focused on other measures such as the efficiency or effectiveness of PV and wind, oftentimes considering total costs and rates of return, total energy input and energy-payback times, and even other environmental measures such as toxicity, carcinogen output, and water consumption, but *not* greenhouse gas emissions.

3.2. Recentness

The second exclusionary condition was that of recentness, which was responsible for the omission of the 10 articles shown in Table 2. Due to the rapid technological progress that has occurred in the efficiency, sizing, and implementation of PV and wind systems over the last decade, a 10 year publication window extending to 2003 was constructed, effectively blocking out all material published beforehand. However, as evidenced in Tables 5 and 8, the earliest retained piece of literature was published in 2004 (the only 2004 inclusion), with only three 2005 studies, and only 12 of the total 41 predating 2008. Although unintentional, more than 70% of the studies are actually within a five year window.

3.3. Peer review

Our third step involved excluding studies that were not formally peer-reviewed. Peer review was thought critical to ensuring the integrity of the analysis. The only literature examined beyond peer reviewed journals came from conference proceedings, which were then checked for peer review by a scientific committee in order to pass this standard. In all, only one conference report – Noori et al. (2012) – was unable to be verified and was removed from the sample for not meeting this condition.

3.4. Originality

The fourth restriction was to exclude 28 studies shown in Table 3 that were not a primary source. Effectively, all articles that did not provide new and original CO_2-eq/kWh information were eliminated to avoid reliance on sources more than once (so as to not skew the analysis), and also to ensure that the other exclusionary criteria were not subverted (e.g., the secondary source could be based on primary information that was not peer reviewed). Other articles were excluded if they included a GHG intensity estimate as a part of a different type of analysis and thus relied on other sources for the numbers, or amalgamated other lifecycle studies and gave a range or average, not significantly unlike this study. A few very detailed studies done in conjunction with the National Renewable Energy Laboratory's (NREL) "Life Cycle Harmonization Project" were included despite this literature compilation approach. Examples include Hsu et al. (2012), Kim et al. (2012) and Dolan and Heath (2012), not to be confused with the NREL factsheets excluded for originality in Table 3. These included studies did much more than simply find a range or average g CO_2-eq/kWh estimate, and instead recalculated estimates from other studies by harmonizing the conditions that the studies assumed, for example by inputting consistent life expectancies, wind speeds or solar irradiance.

Table 3
Lifecycle studies excluded for lack of originality.

Source	Technology	g CO_2/kWh
Arvesen and Hertwich (2012)	Wind	6–34
Bensebaa (2011)	Solar PV	30
Chaurey and Kandpal (2009)	Solar PV	–
Dones et al. (2004)	Wind	10–20
	Solar PV	39–73
Dotzauer (2010)	Wind	9–10
	Solar PV	32
Dufo-Lopez et al. (2011)	Wind, solar PV	–
Evans et al. (2009)	Wind	25
	Solar PV	90
Fthenakis et al. (2008)	Solar PV	24, 30–45, 39–110
Fthenakis and Kim (2011)	Solar PV	38
Georgakellos (2012)	Wind	8.20
	Solar PV	104
Goralczyk (2003)	Wind, solar PV	–
Graebig et al. (2010)	Solar PV	–
Hardisty et al. (2012)	Wind, solar PV	–
Kannan et al. (2007)	Solar PV	217
Kenny et al. (2010)	Solar	21–59
NREL (National Renewable Energy Laboratory) (2012)	Solar PV	40
NREL (National Renewable Energy Laboratory) (2013)	All electricity generation	–
Pacca et al. (2007)	Solar PV	34.3–50
Padey et al. (2012)	Wind	4.5–76.7
Peng et al. (2013)	Solar PV	10.5–50
Raadal et al. (2011)	Wind	17.5
Sherwani et al. (2010)	Solar PV	15.6–280
Tyagi et al. (2013)	Solar PV	9.4–2820
Van der Meulen and Alsema (2011)	Solar PV	–
Varun et al. (2009a)	Wind	9.7–123.7
	Solar PV	53.4–250
Varun et al. (2009b)	Wind	16.5–123.7
	Solar PV	9.4–300
Weisser (2007)	Wind	18
	Solar PV	56
Yang et al. (2011)	Wind	.56

Table 4
Lifecycle studies excluded for failure to consider all GHGs.

Source	Technology	g CO_2/kWh
Garcia-Valverde et al. (2009)	Solar PV	131
Ito et al. (2008)	Solar PV	9–16
Ito et al. (2009)	Solar PV	51.5–71
Ito et al. (2010)	Solar PV	43–54
Kleijn et al. (2011)	Wind	15
	Solar PV	60
Krauter and Ruther (2004)	Solar PV	11–75
Lee and Tzeng (2008)	Wind	3.6
Lenzen and Wachsmann (2004)	Wind	2–81
Li et al. (2012)	Wind	69.9
McMonagle (2006)	Solar PV	0–59
Pehnt et al. (2008)	Wind	22
Sherwani et al. (2011)	Solar PV	55.7
Sumper et al. (2011)	Solar PV	–
Wang and Sun (2012)	Wind	4.97–8.21
Zhai and Williams (2010)	Solar PV	21

3.5. Completeness

A final factor used to screen the literature was for failure to consider the entire range of GHGs, which then led to the removal of 15 articles shown in Table 4. Although these articles generally met the previous requirements, they only attempted to quantify the CO_2 lifecycle emissions attributed to wind and/or solar PV. In the interests of focusing this study on the entirety of GHGs (in order to assess the totality of the global warming potential of wind and solar PV), these articles were excluded.

4. Assessing the greenhouse gas intensity of wind energy

After removing a total of 112 studies based upon our five selection criteria, 41 studies remained which are relevant, published in the past 10 years, peer-reviewed, provided original estimates of total GHG intensity, and incorporated all greenhouse gases. These studies were then disaggregated into those looking at wind and solar PV, with Table 5 presenting those related to wind energy. These studies were "weighed" equally; that is, they were not adjusted for their methodology, time of release within the past ten years, or how rigorously they were peer reviewed or cited in the literature. Additionally, the estimates were not harmonized for divergent variables or assumptions inherent in their analysis. The studies in Table 5 are quite global in nature, spanning at least five continents specifically, and including several studies that were global.

Statistical analysis of these 22 studies and 39 estimates reveals a range of greenhouse gas emissions over the course of wind's lifecycle at the extremely low end of 0.4 g CO_2-eq/kWh and the extremely high end of 364.8 g CO_2-eq/kWh. Accounting for the average values of emissions associated with each part of wind energy's lifecycle, the mean value reported is 34.1 g CO_2-eq/kWh —numbers reflected in Fig. 3 and Tables 6 and 7. As Fig. 1 already depicted in the introduction, cultivation and fabrication are

Table 5
Total lifecycle GHG emissions and factors for 22 qualified wind energy studies.

Source	Location	Life (years)	Onshore/ offshore	System/turbine capacity	Hub height (m)	Rotor diameter (m)	Other assumptions	Total estimate (g CO_2-eq/kWh)
Ardente et al. (2008)	Italy	20	Onshore	11 × 660 kW turbines	55	50		**14.8**
Chen et al. (2011)	Guangxi, China	20	Onshore	24 × 1.25 MW turbines	55	31	7 m/s avg. wind speed	**0.56**
Dolan and Heath (2012)	Global	20	Both		–	–	.25 capacity factor	**11**
Fleck and Huot (2009)	–	20	Onshore	5 × 400 W turbines	30	1.17	Off-grid, with battery bank, .17 capacity factor	**364.83**
Guezuraga et al. (2012)	Global (German, Chinese, Denmark manufacturing)	20	Onshore	1.8 MW gearless turbine	–	–		**8.82**
				2 MW geared turbine	105	90	7.4 m/s avg. wind speed	**9.73**
Hondo (2005)	Japan	30	Onshore	300 kW turbines	–	–	.2 capacity factor	**29.5**
Kabir et al. (2012)	Alberta, Canada	25	Onshore	20 × 5 kW turbines	36.6	5.5	.23 capacity factor	**42.7**
				5 × 20 kW turbines	36.7	9.45	.22 capacity factor	**25.1**
				100 kW turbine	37	21	.24 capacity factor	**17.8**
Khan et al. (2005)	Newfoundland, Canada	20	Onshore	500 kW system	–	–	Turbine, no fuel cell storage	**16.86**
							Turbine with fuel cell storage	**59.31**
Mallia and Lewis (2013)	Ontario, Canada	20	Onshore		–	–	Avg. Canadian electricity mix (210 g CO_2-eq/kWh)	**10.69**
Manish et al. (2006)	India	-	Onshore	18 × 500 kW turbines	–	–	2003 global electricity mix, .1–.3 capacity factor	**12–40**
Martinez et al. (2009a)	Munilla, Spain	20	Onshore	2 MW turbine	70	80		**6.58**
Mithraratne (2009)	Production UK, Installation New Zealand	20	Onshore	1.5 kW turbines	10	2	Roof mounted, .04 – .064 capacity factor, New Zealand electricity mix (224 g CO_2-eq/kWh), 5.5–6.3 m/s avg. wind speed	**138–220**
Oebels and Pacca (2013)	North Eastern Brazil	20	Onshore	14 × 1.5 MW turbines	80	–	Brazilian electricity mix (64 g CO_2-eq/kWh), .3425 capacity factor, 7.8 m/s avg. wind speed	**7.1**
Padey et al. (2013)	Europe	-	Onshore		–	–	–	**12.9**
Pehnt (2006)	Germany	-	Onshore	1.5 MW turbine	–	–	566 g CO_2-eq/kWh electricity mix	**11**
			Offshore	2.5 MW turbine	–	–	566 g CO_2-eq/kWh electricity mix	**9**
Querini et al. (2012)	Global	20	Onshore	2 MW turbine	–	–		**12**
Songlin et al. (2011)	Fuzhou, China	–	–	2 MW turbine	–	–		**0.43**
Tremeac and Meunier (2009)	Southern France	20	Onshore	4.5 MW turbines	124	113		**15.8**
	Production Finland, Installation France	20	Onshore	250 W wind turbines	–	–	Finnish electricity mix	**46.4**
Wagner et al. (2011)	German North Sea	20	Offshore		–	–		**32**
Weinzettel et al. (2009)	–	20	Floating Offshore	40 floating 5 MW turbines	100 (above sea level)	116		**0.89**
Wiedmann et al. (2011)	UK	30	Offshore	2 MW farm	–	–	Process lifecycle analysis, .3 capacity factor	**13.4**
							Integrated hybrid lifecycle analysis, .3 capacity factor	**28.7**
							IO-based hybrid lifecycle analysis, .3 capacity factor	**29.7**
Zimmermann and Gößling-Reisemanna (2012)	Germany	20	Onshore	2.3 MW system	98	80		**7.9**
					84	80	7.5 m/s avg. wind speed	**12.5**
					98	80	7.72 m/s avg. wind speed	**12**
					108	80	7.9 m/s avg. wind speed	**11.2**
					98	80	7.9 m/s avg. wind speed	**10.8**
					108	80	8.15 m/s avg. wind speed	**10.1**
					98	80	8.14 m/s avg. wind speed	**9.8**
					108	80	8.57 avg. wind speed	**8.3**

responsible for about 71% of wind's emissions, followed by construction (24%), operation (slightly less than 24%), and decommissioning, which offset 19.1 percent of wind's emissions.

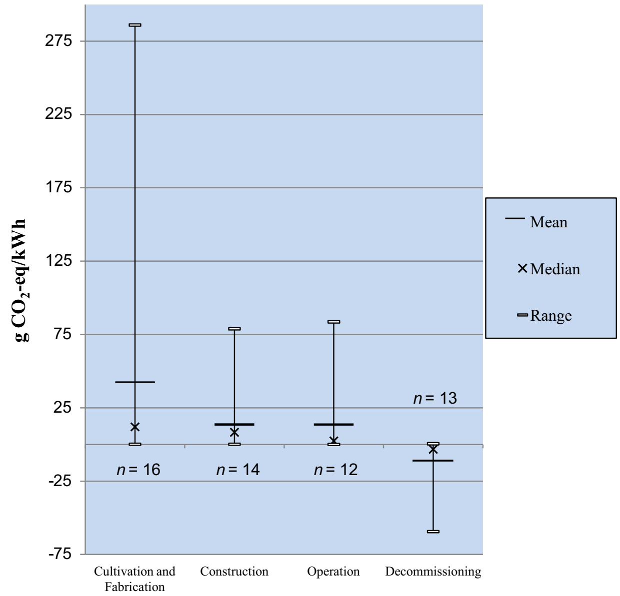

Fig. 3. Lifecycle greenhouse gas emissions for wind energy by lifecycle stage.

5. Assessing the greenhouse gas intensity of solar PV

Sticking with the same selection process, Table 7 presents the 23 most relevant, recent, peer-reviewed, original, and complete studies for solar PV. These studies, similar to those for wind energy, were weighted equally. Estimates were also not harmonized for different assumptions or variables. The studies in Table 8 are also quite global in nature, spanning three continents and/or the globe.

Statistical analysis of these 23 studies and 57 estimates reveals a range of greenhouse gas emissions over the course of solar PV's lifecycle at the extremely low end of 1 g CO_2-eq/kWh and the high end of 218 g CO_2-eq/kWh. Accounting for the average values of emissions associated with each part of solar PV's lifecycle, the mean value reported is 49.9 g CO_2-eq/kWh – numbers reflected in Fig. 4 and Tables 9 and 10 – though the number of selected studies providing estimates for operation and maintenance (2) and decommissioning (5) is low. As Fig. 1 also depicted in the introduction, cultivation and fabrication are responsible for about 71% of solar PV's emissions, followed by construction (19%), operation (13%), and decommissioning, which offset 3.3% of emissions.

6. What causes the disparity in wind and solar estimates?

Though the tables and figures above do a satisfactory job documenting the lifecycle emissions associated with wind energy

Table 6
Summary statistics of qualified studies reporting projected greenhouse gas intensity for wind energy.

	Cultivation and fabrication ($n=16$)	Construction ($n=14$)	Operation ($n=12$)	Decommissioning ($n=13$)	Total ($n=39$)
Mean	42.98	14.43	14.36	−11.64	34.1
Median	11.99	8.26	2.37	−3.27	12
Mode	–	9	–	–	12
Std. Dev.	76.95	21.17	26.3	18.76	67.23
High	286.02	78.85	83.6	0.5	364.8
Low	0.15	0.15	0.02	−59.4	0.4
Percentage of Total (%)	71.48	24.00	23.88	−19.36	100

Note that the “total” column equals the mean for all lifecycle studies that made it past our screen, not necessarily those that broke emissions down by specific lifecycle stages. “n” also refers to number of estimates, not necessarily number of studies.

Table 7
Detailed statistics of qualified studies reporting lifecycle equivalent greenhouse gas intensity for wind energy.

Source	Cultivation and fabrication	Construction	Operation	Decommissioning	Total
Chen et al. (2011)	0.15	0.42	0.02	–	0.56
Fleck and Huot (2009)	286.02	78.85	–	–	364.83
Guezuraga et al. (2012)	7.89	–	–	–	8.82
	7.59	–	–	–	9.73
Hondo (2005)	13.7	7.4	8.3	–	29.5
Kabir et al. (2012)	30.74	9.11	14.8	−11.96	42.7
	12.01	12.55	3.82	−3.27	25.1
	11.97	10.13	0.92	−5.22	17.8
Mallia and Lewis (2013)	–	–	0.74	0.27	10.69
Martinez et al. (2009a)	6.96	2.01	0.35	−2.75	6.58
Mithraratne (2009)	98	24.1	52.4	−37.2	138
	156.2	37.4	83.6	−59.4	220
Oebels and Pacca (2013)	5.31	1.75	0.04	–	7.1
Songlin et al. (2011)	0.27	0.15	–	–	0.43
Tremeac and Meunier (2009)	–	–	0.8	−3.6	15.8
	–	–	–	−29.5	46.4
Wagner et al. (2011)	–	–	6.5	0.4	32
Wiedmann et al. (2011)	9.5	3	–	0.43	13.4
	22.5	4.8	–	0.5	28.7
	18.8	10.3	–	0.01	29.7

Table 8
Total lifecycle GHG emissions and factors for 23 qualified solar PV studies.

Source	Location	Life (years)	Irradiance (kWh/m^2)	Tech	Mounting	Assumptions	Estimate (g CO_2-eq/kWh)
Alsema and de Wild-Scholten (2004)	Southern Europe	–	–	Ribbon-Si	–		**28**
	Netherlands/Germany	–	–	Ribbon-Si	–		**48**
	Southern Europe	–	–	Multi-Si	Roof mount		**73**
	Netherlands/Germany	–	–	Multi-Si	Roof mount		**124**
Alsema et al. (2006)	Production US, Installation Southern Europe	30 (15 inverter)	1700	CdTe	Ground mount	9% efficiency	**25**
	Southern Europe	30 (15 inverter)	1700	Ribbon-Si	Roof mount	11.5% efficiency	**29.5**
				Mono-Si	Roof mount	14% efficiency	**35**
				Multi-Si	Roof mount	13.2% efficiency	**32**
Beylot et al. (2014)	-	30	1700	Multi-Si	30° tilt, fixed aluminum mount	5 MWp, 14% module efficiency	**53.5**
					30° tilt, fixed wood mount	5 MWp, 14% module efficiency	**38**
					30° tilt, single axis tracking	5 MWp, 14% module efficiency	**37.5**
					30° tilt, dual axis tracking	5 MWp, 14% module efficiency	**42.8**
Bravi et al. (2011)	Europe	20	1700	Micromorph	22° roof mount	125 Wp module, 8.74% efficiency, 513 g CO2/kWh European electricity mix	**20.9**
Desideri et al. (2013)	Sicily, Italy	30	1600–1800	Mono-Si	30° tilt, ground mounted single-axis tracking	13.85% module efficiency, 2 MWp	**47.9**
de Wild-Scholten et al. (2006)	Southern Europe	30 (15 inverter)	1700	Multi-Si	on-roof Phonix mounting structure	11.4 kWp, 13.2% module efficiency	**38**
					on-roof Schletter roof hooks	11.4 kWp, 13.2% module efficiency	**35.5**
					in-roof Schletter mounting structure	11.4 kWp, 13.2% module efficiency	**32**
					in-roof Schweizer mounting structure	11.4 kWp, 13.2% module efficiency	**32.5**
					ground Phonix mount	11.4 kWp, 13.2% module efficiency	**41**
					ground Springerville mount	11.4 kWp, 13.2% module efficiency	**37**
Espinosa et al. (2011a)	Manufacturing Denmark, Installation Southern Europe	15	1700	Transparent organic polymer, indium-tin-oxide (ITO)	-	2% module efficiency, 2008 Denmark energy mix (420.88 g CO_2-eq/kwh)	**37.77**
						3% module efficiency, 2008 Denmark energy mix (420.88 g CO_2-eq/kwh)	**56.65**
Fthenakis and Alsema (2006)	Europe	30	1700	Multi-si	On-roof mount	european electricity mix 13.2% efficiency	**37**
				CdTe	On-roof mount	european electricity mix, 8% efficiency	**21**
				Ribbon-Si	On-roof mount		**30**
				mono-Si	on-roof mount		**45**
	Production US, Installation Europe	30	1700	CdTe	ground mount	US electricity mix, 9% efficiency	**25**
Fthenakis and Kim. (2006)	United States	30	1800	CdTe	Ground mount	25 MWp, 9% efficiency	**24**
Fthenakis et al. (2009b)	Ohio, USA	–	1700	CdTe	–	10.9% efficiency, US electricity mix (750 g CO_2-eq/kWh)	**12.75**
Garcia-Valverde et al. (2010)	Southern Europe	15	1700	Organic/plastic	–	5% module efficiency	**109.84**
Glockner et al. (2008)	Europe	30	1700	Multi-Si	On-roof mount Schletter mounting	Siemens Si processing, 13.2% module efficiency	**30**
						Elkem Solar Si processing, 13.2% module efficiency	**23**
Hondo (2005)	Japan	30	–	Poly-Si	On-roof mount	3 kWp, 0.15 capacity factor, 10% efficiency	**53.4**
Hsu et al. (2012)	Global	30	1700	c-Si	–		**45**
				mono-Si	–	14% module efficiency	**40**
				Multi-Si	–	13.2% module efficiency	**47**
				c-Si	Ground mount		**48**
				c-Si	Roof mount		**44**
Jungbluth (2005)	Switzerland	30	1100	Poly-Si	On-roof mount	3 kWp, 79 g CO_2-eq/kWh electricity mix	**39–110**
Kannan et al. (2006)	Singapore	25	1635	Mono-Si		2.7 kWp	**217**

Table 8 (*continued*)

Source	Location	Life (years)	Irradiance (kWh/m^2)	Tech	Mounting	Assumptions	Estimate (g CO_2-eq/kWh)
					Aluminum/concrete roof mount		
Kim et al. (2012)	Global	30	2400	a-Si	Ground mount	6.3% efficiency	**20**
				CdTe	Ground mount	10.9% efficiency	**14**
				CIGS	Ground mount	11.5% efficiency	**26**
				a-Si	On-roof mount	6.3% efficiency	**21**
				CdTe	On-roof mount	10.9% efficiency	**14**
				CIGS	On-roof mount	11.5% efficiency	**27**
Manish et al. (2006)	India	20	–	–	–	10–15% efficiency	**50–130**
Pehnt (2006)	Germany	25	–	Poly SOG-Si	–	566 CO_2-eq/kWh electricity mix	**104**
Querini et al. (2012)	Global	30	1204	Mono-Si	45 degree fixed mount		**92**
Reich et al. (2011)	–	30	1300	c-Si	–	no F-gas emissions, renewable electricity mix (1 g CO_2-eq/kWh), 15% efficiency	**1**
						coal electricity mix without CCS (1,000 g CO_2-eq/kWh), 15% efficiency	**218**
Sengul and Theis (2011)	Europe	30	1700	CdSe QDPV	Ground mount	14% efficiency	**5**
Veltkamp and de Wild-Scholten (2006)	Southern Europe	5	1700	Glass–glass (DSC) dye sensitizes	–	8% efficiency	**106.25**
		10	1700		–	8% efficiency	**52.5**
		20	1700		–	8% efficiency	**17.5**

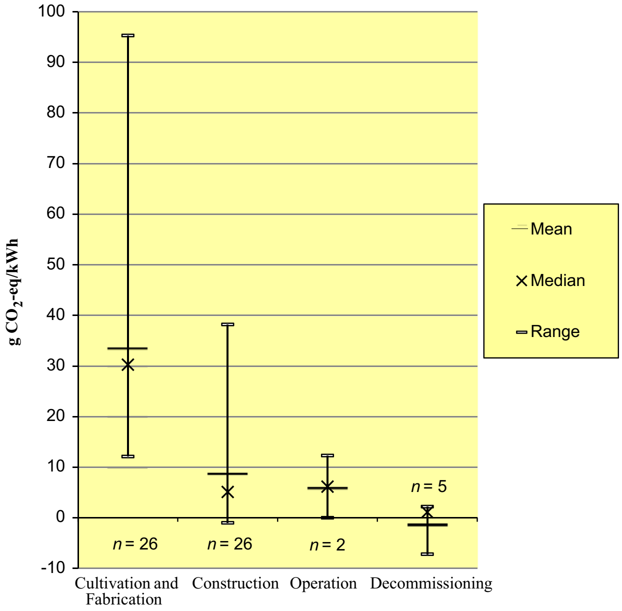

Fig. 4. Lifecycle greenhouse gas emissions for solar PV by lifecycle stage.

and solar PV systems from our "best" sample of studies, substantial disparities do exist, and this section of the study explains how at least eight separate factors play a role in these differences: (1) resource inputs and technology, (2) transportation, (3) manufacturing, (4) location, (5) sizing and capacity, (6) longevity, (7) optional equipment, and (8) calculation methods.

6.1. Resource inputs and technology

The material inputs required for wind generation necessarily vary in the literature based upon physical size (capacity and hub height), the location and design of the plant (onshore versus offshore and interconnection distances), and even based upon the type of technology used (floating turbines, turbines with and without gearboxes, etc.). Guezuraga et al. (2012) compares two turbines, one 2 MW geared turbine and one 1.8 MW gearless turbine, and found significantly higher stainless steel, reinforced concrete and total mass calculations (1538 t) for the former, and higher copper requirements, but overall lower mass (360 t) for the latter. Intuitively, these sorts of differences alter the GHG intensity of the manufacturing and construction lifecycle stages. Also, despite presumably greater material inputs required by offshore wind installations to reach the seabed and the general presumption that they are generally larger turbines to take advantage of higher wind speeds, offshore estimates in the literature show decreased emissions intensity. While there was a much larger estimate sample for onshore (31 compared to 6), and some obvious outliers, offshore estimates showed a lower mean intensity illustrated by Fig. 5.

Similarly, PV technologies vary substantially in their emissions profiles, given that they require somewhat different material inputs. Our sample of studies included crystalline silicon technologies such as mono-crystalline (mono-Si), poly-crystalline (poly-Si), multi-crystalline (multi-Si) and ribbon multi-crystalline (ribbon-Si), as well as several thin-film technologies such as amorphous silicon (a-Si), cadmium telluride (CdTe) and copper–indium–gallium–diselenide (CIGS). The sample also included other PV types such as micromorph (a-Si and micro-Si hybrid), organic/plastic cells (including indium-tin-oxide, dye sensitized and others), and cadmium selenide quantum-dot photovoltaics (CdSe QDPV). All of these technologies have distinct material and processing requirements,

Table 9
Summary statistics of qualified studies reporting projected greenhouse gas emissions for solar PV.

	Cultivation and fabrication	Construction	Operation	Decommissioning	Total
	(*n*=26)	(*n*=26)	(*n*=2)	(*n*=5)	(*n*=57)
Mean	33.67	8.98	6.15	−1.56	49.9
Median	30.25	5.1	6.15	1.1	37.8
Mode	16, 21.3, 33, 36	2	–	2.2	14, 21, 25, 30, 32, 37, 38, 45, 48
Standard Deviation	20.57	10.15	8.7	4.68	43.3
High	95.31	38.2	12.3	2.2	218
Low	12.1	−1	0	−7.2	1
Percentage of total (%)	71.30	19.00	13.00	−3.30	100

Note that the “total” column equals the mean for all lifecycle studies that made it past our screen, not necessarily those that broke emissions down by specific lifecycle stages. “*n*” also refers to number of estimates, not necessarily number of studies.

Table 10
Detailed statistics of qualified studies reporting lifecycle equivalent greenhouse gas emissions for solar PV.

Source	Cultivation and fabrication	Construction	Operation	Decommissioning	Total
Alsema et al. (2006)	25.4	4.1	–	–	29.5
	28.7	3.3	–	–	32
	31.8	3.2	–	–	35
	18.75	6.25	–	–	25
Beylot et al. (2014)	21.3	38.2	–	−6.1	53.5
	21.3	15.6	–	1.1	38
	20.2	23.2	–	2.2	37.5
	16	24.6	–	2.2	42.8
de Wild-Scholten et al. (2006)	37	1	–	–	38
	33.5	2	–	–	35.5
	33	−1	–	–	32
	33	−0.5	–	–	32.5
	36	5	–	–	41
	36	1	–	–	37
Fthenakis and Alsema (2006)	32.5	4.5	–	–	37
	16	5	–	–	21
	19	6	–	–	25
Glockner et al. (2008)	28.1	2	–	–	30
	20.9	2	–	–	23
Hondo (2005)	28.3	9.8	12.3	–	53.4
Jungbluth (2005)	33.8–95.31	5.19–14.66	0	–	39-110
Querini et al. (2012)	85.6	6.3	–	−7.2	92
Veltkamp and de Wild-Scholten (2006)	75	31.3	–	–	106.25
	36.9	15.6	–	–	52.5
	12.1	5.3	–	–	17.5

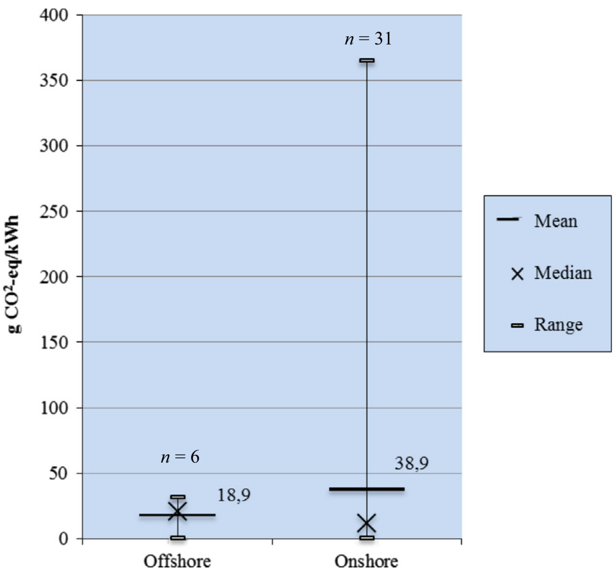

Fig. 5. Differences in greenhouse gas intensity for onshore and offshore wind turbines.

leading to different solar conversion efficiencies in the final product, and thus an exceptional range of emissions possibilities for PV as a whole—statistics reflected in Table 11. Table 11 shows mono-Si to have the highest average estimated emissions and CdSe QDPV ranks as having the lowest emissions, though the sample sizes of the studies behind these claims are small.

6.2. Transportation

While transportation – a subcomponent of our construction lifecycle stage – might not seem like a major GHG producing aspect of either wind or solar PV, there is significant variation in the literature. For wind, the highest transportation estimate accounted for 28.3% of total emissions (Mallia and Lewis, 2013), whereas the average percentage share of transportation is significantly lower, at only 11.8%, and the lowest estimates fall to as small as 0.2% (Chen et al., 2011). There are a number of factors that can explain this variation. First, assessments of smaller turbines that include battery backup and additional optional equipment, potentially manufactured and transported separately from different locations, and overall producing less lifetime energy than large multi-megawatt turbines, show a higher than average share of transportation GHGs. For

Table 11
Differences in greenhouse gas intensity based on solar PV material inputs.

PV technology	Mean	Median	*n*	Mode	Standard deviation	High	Low
Mono-Si	**79.5**	46.5	6	–	70.4	217.0	35.0
Multi-Si	**44.3**	37.5	17	32, 37, 38	23.3	124.0	23.0
Poly-Si	**78.7**	78.7	2	–	35.8	104.0	53.4
Ribbon	**33.9**	29.8	4	–	9.5	48.0	28.0
Total c-Si	**55.3**	40.5	34	30, 32, 37, 38, 45, 48	47.1	218.0	1.0
a-si	**20.5**	20.5	2	–	0.7	21.0	20.0
CIGS	**26.5**	26.5	2	–	0.7	27.0	26.0
CdTe	**19.4**	21.0	7	14, 25	5.6	25.0	12.8
Total thin-film	**20.9**	21.0	11	14	5.2	27.0	12.8
Organic ITO	**47.2**	47.2	2	–	13.4	56.7	37.8
Dye sensitized	**58.8**	52.5	3	–	44.7	106.3	17.5
Total organic	**63.4**	54.6	6	–	37.2	109.8	17.5
CdSe QDPV	**5.0**	5.0	1	–	–	5.0	5.0
Micromorph	**20.9**	20.9	1	–	–	20.9	20.9

example, Fleck and Huot (2009) find a large 78.85 g CO_2-eq/kWh, equating to 21.5% of lifecycle intensity, resulting from transportation for very small 400 W turbines with battery backup. Further transportation discrepancies could arise between onshore and offshore turbines as they necessarily entail different transportation processes, types (boat, airplane, rail, truck) and distances involved.

PV lifecycle studies seemingly focused significantly less on defining the GHG intensity of transportation, which is a clear weakness of the literature as a whole. Although the same theoretical implications as considered for wind systems should apply, the only individual estimate specifically for transportation was that of Querini et al. (2012), which found 6.3 g CO_2-eq/kWh accounting for 6.9% of the total emissions profile.

6.3. Manufacturing

Fabrication and manufacturing are energy intensive processes which may partially depend on direct fossil fuel use, generally for heating processes, but also significantly rely on electricity inputs. One assumption found throughout wind and PV literature relates to the electricity mix of the locale, considering the types of electricity generators (coal, natural gas, nuclear, renewables) which supply the local grid. Depending upon how carbon intensive these sources are, wind and solar estimates vary.

In the case of wind, Guezuraga et al. (2012) showed that the same manufacturing process in Germany would result in less than half of the total emissions that such a process would entail in China. This was primarily due to China's significantly greater dependence on black coal for electricity production in comparison with Germany's much greater reliance on natural gas and nuclear power. Oebels and Pacca (2013) also attributed significant disparity to the location of manufacturing, noting that the Brazilian electricity mix, being as low as 64 g CO_2-eq/kWh (as much as eight times lower than the global average), had a significant effect on their low overall calculation (7.1 g CO_2-eq/kWh). This contrasts with Pehnt (2006) which used a 566 g CO_2-eq/kWh energy mix and returned a 9–11 g CO_2-eq/kWh wind calculation, a 55% increase to Oebels and Pacca (2013).

For PV, this trend again applies as PV manufacturing also depends upon electricity to compose finished modules. Some energy mix assumptions made in the literature include a Danish grid intensity of 420.88 g CO_2-eq/kWh (Espinosa et al., 2011a) and a 566 g CO_2-eq/kWh for Germany (Pehnt, 2006). One study that pays explicit attention to this factor, Reich et al. (2011), concludes that the source of the electricity mix can affect the GHG intensity of a PV installation anywhere from zero g CO_2-eq/kWh (for an all renewable and nuclear mix) to 200 g CO_2-eq/kWh (for coal-only mixes). Manufacturing can also see emissions intensity variation based upon the particular type of PV technology considered and its relevant processing steps. For example, quartz extraction from sand and then processing and refinement are needed to create PV grade silicate for some panels, whereas others such as CIGS may not need silicates at all. Other influential factors include the type of PV technology. For amorphous, multi, and mono PV systems, silicates may need to be converted into different products, such as ingots, wafers, or other components, to form the finished panel (Glockner et al., 2008). Accordingly, the amount of energy and GHG emissions attributable to all of these processes can lead to significant variation.

6.4. Location

Emissions efficiency is directly tied to geographic location and the solar and wind resource base. Essentially, the more of the resource, the more power generation and therefore the lower the GHG intensity. For wind turbines, wind is subject to signification spatial variation, both globally and locally, and also to temporal variation, in terms of seasonal and daily fluctuations. These factors strongly influence the total amount of electricity generated and thus are important variables assumed in the literature to calculate the GHG intensity of wind turbines. Most global average wind speed maps shows that oceans, especially in the far North and South, have higher wind speed averages, along with mountainous and coastal areas (3Tier Inc., 2011b). Furthermore, local topography plays a role in wind speeds and availability, as mountains, manmade structures, and even vegetation (for smaller turbines) can affect airflow. Zimmermann and Gößling-Reisemanna (2012) pay particular attention to this factor and show how different hub heights on the same sited turbine leads to different average wind speeds, from 7.5 m/s to 8.57 m/s, which then leads to fluctuation in overall CO_2-eq/kWh, from 8.3 g to 12.5 g. Despite the critical implications that wind speed can have between otherwise similar turbines, this factor is clearly not the most important consideration (as compared to sizing, on/offshore and lifetime) as the unharmonized statistics taken from the literature do not show an obvious trend.

The location of PV installations has the same implications. Solar resources vary both globally and locally across the world, and again vary on a daily and seasonal basis. Shading problems caused by local geography, vegetation, and structures can thus play a role on solar PV performance (3Tier Inc., 2011a). Therefore, though most studies presumed a solar irradiance value of 1700 kWh/m^2/yr, some in our sample went as low as 1100 kWh/m^2/yr whereas others assumed 2400 kWh/m^2/yr (more consistent with the

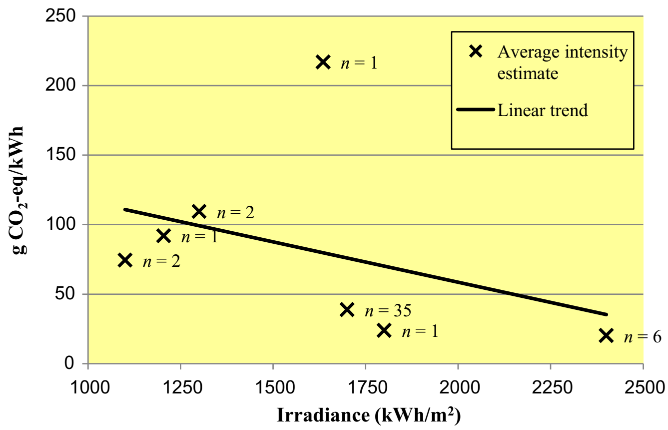

Fig. 6. Differences in greenhouse gas intensity for solar PV based on irradiance.

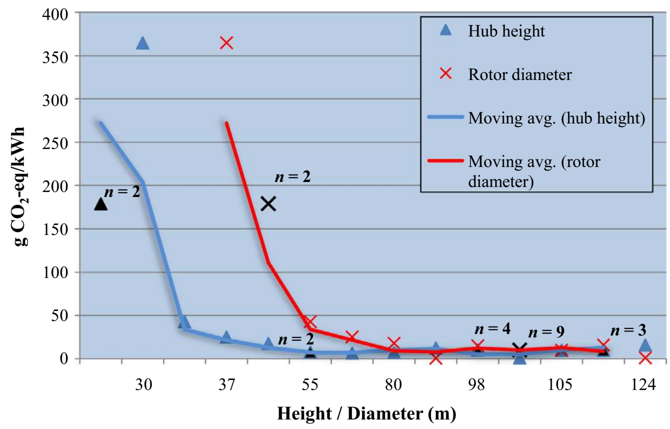

Fig. 8. Differences in greenhouse gas intensity for wind energy based on hub height and rotor diameter. *Note*: to avoid excessive data labels, *n* values are not provided for data points that represent individual estimates from the literature. Instead, only data points that represent an average GHG intensity from multiple estimates in the literature are labeled with the appropriate *n* value, and the data points are presented in black for specificity.

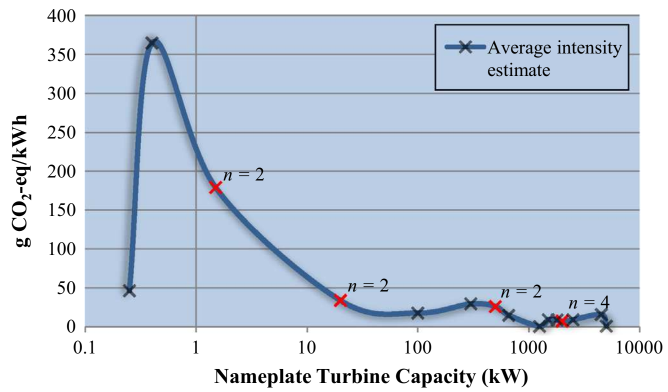

Fig. 7. Differences in greenhouse gas intensity for wind energy based on nameplate capacity. *Note*: to avoid excessive data labels, *n* values are not provided for data points that represent individual estimates from the literature. Instead, only data points that represent an average GHG intensity from multiple estimates in the literature are labeled with the appropriate *n* value, and the data points are presented in red for specificity.

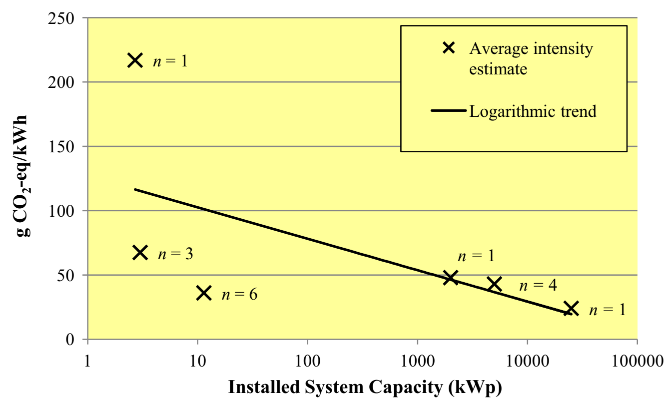

Fig. 9. Differences in greenhouse gas intensity for solar PV based on installed system capacity.

Sahara or the American Southwest). Fig. 6 illustrates how solar irradiance has a direct effect on greenhouse gas intensity.

6.5. Sizing and capacity

The literature reveals differences in emissions intensity based upon the physical and nameplate capacity sizes of each system, with a positive trend as sizes increase. Higher capacity wind turbines, both with taller hub heights and larger rotor diameters, correspond to lower GHG intensities. Tremeac and Meunier (2009) compared a 4.5 MW turbine to a 250 W version and found the smaller to have a GHG intensity equal to approximately three times greater than the larger turbine. Kabir et al. (2012) calculates that 20 × 5 kW turbines result in an emissions intensity of 42.7 g, 5 × 20 kW turbines have an emissions intensity of 25.1 g, and one 100 kW turbine has a mere 17.8 g of CO_2-eq/kWh, implying that “bigger is better.” Figs. 7 and 8 plot the relationship between greenhouse gas emissions intensity and nameplate capacity and hub height, respectively.

PV, perhaps oddly, also follows the sizing advantages of wind energy. (We say “oddly” because PV is a modular technology that is supposed to work the “same” regardless of whether ten panels or 100 panels are being used). There do appear to be economy of scale advantages that larger PV installations benefit from, possibly due to efficiency gains in logistics and transportation, and with larger systems being able to access a wider (and more stable) solar resource. Per the logarithmic average shown in Fig. 9, there is a clearly downward trend as installed capacity increases from small distributed generation scale installations to larger utility- and merchant-scale power plant projects.

6.6. Longevity

Longevity is a fairly obvious factor influencing GHG intensity. Yet it is also an imprecise one because there are a number of unknown considerations, such as how well maintained the generators are, how well they are manufactured, the physical and natural conditions at the installation site, and how quickly the installations and their interconnections degenerate. Furthermore, because most wind and solar systems have not (yet) been deployed for full lifespans, many estimates are little more than educated guesses.

For the wind literature, lifetime estimates vary in 5–10 year increments between the maximum of 30 years and the minimum of 20 years. Despite the fact that Padey et al. (2012) was excluded for its reliance on secondary sources, it is one of the only studies which specifically looks at the effects of life expectancy on the GHG intensity of an otherwise similar turbine, and shows exactly 50% decreases in GHG intensity for doubled life expectancy estimates, and 66% reductions for tripled estimates. This generally makes sense as doubling life expectancy should nearly double total output, however it does not seem to account completely for

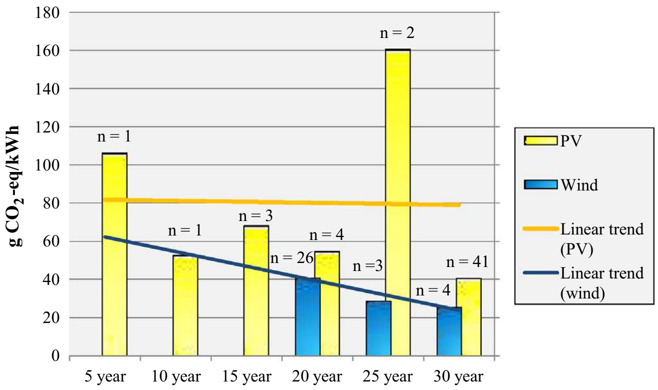

Fig. 10. Differences in greenhouse gas intensity for wind energy and solar PV based on longevity.

increased maintenance and any grid curtailment or degradation of the turbine. As a whole, our sample of the wind literature does show a clear trend, where 20 year assumptions result in an average of 40.69 g CO_2-eq/kWh, 25 years decreases the mean intensity to 28.53 g CO_2-eq/kWh, and 30 years drops it to 25.33 g CO_2-eq/kWh.

The same trend is confirmed by our sample of PV literature, which tended to presume systems operated for 30 years. However, Veltkamp and de Wild-Scholten (2006) showed that a 5 year operating lifetime resulted in an emissions intensity of 106.25 g CO_2-eq/kWh, whereas a 20 year lifetime saw emissions drop to 17.5 g CO_2-eq/kWh—emphasizing the importance of maintenance. When our sample of literature is aggregated as a whole, a linear trend line shows a slight decrease in GHG intensity as lifetime increases, which would clearly be more distinct if the 217 g CO_2-eq/kWh provided by Kannan et al. (2006) in the 25 year PV categoy were harmonized. Fig. 10 details these effects both for wind and solar PV.

6.7. Storage and mounting

One clear factor influencing lifecycle estimations involved optional energy storage. For example, Khan et al. (2005) found that a turbine integrated with fuel cell electricity storage outputted 59.31 g CO_2-eq/kWh, and Fleck and Huot (2009) found a small wind turbine with battery backup to generate 364.83 g CO_2-eq/kWh. These results of course are well above the mean or median wind GHG intensity numbers in the literature. At least one piece of literature, Browne (2010), did attempt to factor in backup power plants potentially needed to supplement wind systems due to intermittency, however this study was excluded for failure to account for GHG intensity (see Table 1). Otherwise, none of the studies included in further analysis appeared to consider this issue.

Also – and perhaps peculiarly – the PV literature did not discuss the need for supplemental production, nor did it investigate battery backup. The PV literature instead tended to focus on the type of mounting that the system required. Many types of roof mounts appear in the literature, including Schletter hooks, Phonix mounting structures and in-roof options (as opposed to on-roof). Fixed ground mounting is also considered in some studies, with various material options including woods and metals (Beylot et al., 2014). Finally, both single-axis and dual-axis tracking options are considered in the literature, which track the sun over the course of the day to maximize exposure and increase productivity per day. According to one study, even given all of the same conditions and components otherwise, ground mounting results in a solar footprint of 53.5 g CO_2-eq/kWh whereas tracking lowers the footprint

Table 12
Differences in greenhouse gas intensity for solar PV based on mounting.

	Roof mount	Ground mount*	Dual axis tracking	Single axis tracking
Mean	48.5	34.5	42.8	42.7
Median	33.8	26	42.8	42.7
n	24	13	1	2
Mode	21, 30, 32	25	–	–
Std. dev.	44.5	21.9	–	7.4
High	217	92	42.8	47.9
Low	14	5	42.8	37.5

* Includes any "fixed mounting" described in the literature not specified as roof.

to 37.5 g CO_2-eq/kWh, clearly a substantial difference (Beylot et al., 2014). Regardless, the statistics compiled into Table 12 do suggest that fixed ground mounting is generally much lower in terms of GHG intensity than roof mounting, which are in turn slightly better than tracking systems (though the sample of studies with data on tracking was very small).

6.8. Calculation methods

Lastly, although not technically related to the "real" GHG emissions intensity of a wind turbine or solar panel, the particular methods utilized in each study were also a cause for variation. Authors from our sample relied on various lifecycle techniques including CML methods (named based upon its founding institution, the Centre for Environmental Studies at the University of Leiden), IO (input–output), hybrid methods, International Organization of Standardization (ISO) methods, and so on. Furthermore, they relied on a variety of different software including different versions of SimaPro and GaBi, as well as different lifecycle and materials databases, such as the popular EcoInvent Database. The best evidence that these different methods result in differing wind estimates is represented in Wiedmann et al. (2011), wherein process analysis, integrated hybrid analysis, and IO hybrid analysis are examined. That study comes to three very different conclusions ranging from 13.4 g CO_2-eq/kWh to 29.7 g CO_2-eq/kWh, all stemming from the particular method used. In the PV literature, none of the studies in our sample specifically addressed this issue, though one article excluded for completeness, Zhai and Williams (2010), contrasted process and hybrid lifecycle methods, finding an end calculation difference of 8 g CO_2/kWh, equivalent to a 38.1% difference in emissions.

7. Conclusions

This study has screened 153 lifecycle studies of greenhouse gas equivalent emissions for wind turbines and solar panels to identify a subset of the 41 most relevant, current, peer-reviewed, original, and complete assessments. It finds a range of emissions intensities for each technology, from a low of 0.4 g CO_2-eq/kWh to a high of 364.8 g CO_2-eq/kWh for wind energy, with a mean value of 34.11 g CO_2-eq/kWh. For solar energy, it finds a range of 1 g CO_2-eq/kWh to 218 g CO_2-eq/kWh, where the mean value is 49.91 g CO_2-eq/kWh. Thus, wind and solar energy are in no way "carbon free" or "emissions free," even though, as Table 13 indicates, they can certainly be called "low-carbon." Based upon these estimates, we make three conclusions.

The first, and perhaps most blatant conclusion, is that lifecycle studies of greenhouse gas emissions associated with the wind and solar energy lifecycles – similar to those for nuclear

Table 13
Comparative lifecycle estimates for sources of electricity.

Technology	Capacity/configuration/fuel	Mean estimate (g Co_2e/kWh)
Hydroelectric	3.1 MW, Reservoir	10
Biogas	Anaerobic Digestion	11
Hydroelectric	300 kW, Run-of-River	13
Solar Thermal	80 MW, Parabolic Trough	13
Biomass	Forest Wood Co-combustion with hard coal	14
Biomass	Forest Wood Steam Turbine	22
Biomass	Short Rotation Forestry Co-combustion with hard coal	23
Biomass	Forest Wood Reciprocating Engine	27
Biomass	Waste Wood Steam Turbine	31
Wind	Various sizes and configurations	34
Biomass	Short Rotation Forestry Steam Turbine	35
Geothermal	80 MW, Hot Dry Rock	38
Biomass	Short Rotation Forestry Reciprocating Engine	41
Solar Photovoltaic	Various sizes and configurations	50
Nuclear	Various reactor types	66
Natural Gas (Conventional)	Various combined cycle turbines	443
Natural Gas (Fracking)	Combined cycle turbines using fuel from hydraulic fracturing	492
Natural Gas (LNG)	Combined cycle turbines utilizing LNG	611
Fuel Cell	Hydrogen from gas reforming	664
Diesel	Various generator and turbine types	778
Heavy Oil	Various generator and turbine types	778
Coal	Various generator types with scrubbing	960
Coal	Various generator types without scrubbing	1,050

Note: Wind and solar PV numbers taken from this study. Hydrofracking numbers taken from Hultman et al. (2011), who argue that shale gas has emissions 11% greater than ordinary natural gas. All other numbers taken from Sovacool (2008).

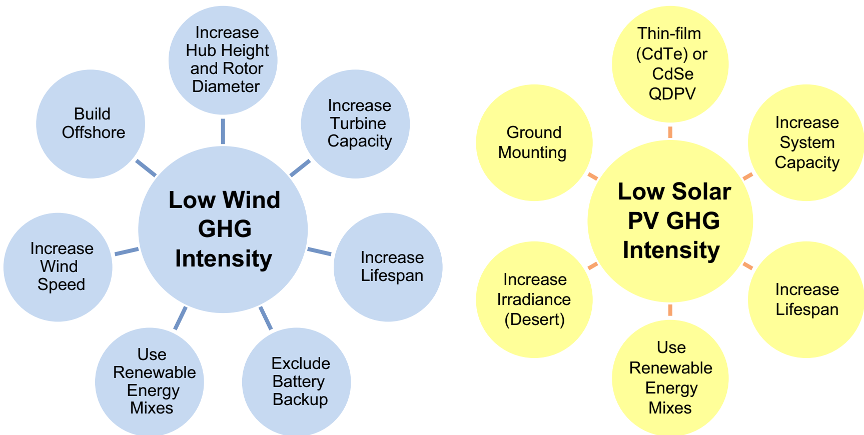

Fig. 11. Low GHG attributes of wind energy and solar PV systems.

power (Sovacool, 2008) – need to become more methodologically rigorous. Of the original 153 articles, 38% were studies that failed to consider greenhouse gas emissions intensity when considering lifecycle impacts. More than 25% of these 153 studies were either outdated, non-peer reviewed, or unoriginal, and another 10% did not consider all greenhouse gases. This left us with only about one-quarter of the available literature. Even within this smaller base of selective literature, the types of lifecycle stages and the ways in which they were defined were dissimilar, and embodied varying assumptions related to a multitude of factors such as resource inputs, manufacturing and fabrication, sizing and capacity, and longevity, among others. Moreover, these studies raise a pressing concern regarding energy storage. On the one hand, storage can alleviate some of the intermittency issues that prevent wind and solar from gaining a greater market share. On the other hand, our analysis suggests that adding storage can increase the GHG intensity of both solar PV and wind energy systems. So if the choice is to be smaller amounts of wind/solar (without storage) and more fossil fuels, or larger amounts of wind/solar (with storage) and less fossil fuels then which option has the overall lower GHG emissions? The current literature leaves this salient question all but unaddressed.

Second, specific configurations of both wind and solar bring with them particular greenhouse gas advantages and disadvantages. A 2 MW wind turbine without battery backup and a 30 year lifetime results in an incredibly low emissions profile of 0.4 g CO_2-eq/kWh. Yet a tiny 400 W, 30 m high, 1.17 m rotor, onshore wind turbine with battery backup and a short 20 year lifetime results in a high emissions profile of 364.8 g CO_2-eq/kWh, approaching that of natural gas. Similarly, a solar PV system produced without F-gasses using an all renewable energy mix was found to have an emissions intensity as low as 1 g CO_2-eq/kWh, whereas a solar PV system produced with F-gasses on a completely coal fired energy mix without carbon capture and storage had an emissions intensity of 218 g CO_2-eq/kWh. These, along with a number of other findings, suggest that the “best” solar and wind systems, those that have the lowest lifecycle greenhouse gas emissions, are those with the attributes characterized by Fig. 11.

Third, and perhaps most important, by looking at these disparities, and drawing from these two conclusions, a number

of important concepts are revealed about how to most effectively utilize wind and PV to combat climate change. It would appear that wind energy is generally a better option for bulk power, and when it comes to this technology, size is key—bigger truly is better (though not too large as to negate the benefits of decentralization). Utility and merchant-power-plant sized turbines with larger rotors and higher nameplate capacities, as well as those placed higher and out to sea to take advantage of stronger wind speeds, are generally the best performing options (from an emissions standpoint). For solar PV, the GHG intensity benefits seem to lie in more in the use of cadmium telluride, CdSe QDPV, and micromorph technologies, sited in deserts, with ground mounting and possibly single or dual-axis tracking. The literature also suggests that battery and fuel cell electricity storage have a substantially negative implication for emissions intensity of wind systems, and despite the lack of information available for PV, the same logical concerns apply, making grid connection without storage possibly better options (from a greenhouse gas standpoint, again). Better understanding, and researching, these sorts of factors will be critical to enhancing the ability for wind energy and solar PV to effectively mitigate greenhouse gas emissions.

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